

ON WIDENING THE ANGULAR EXISTENCE DOMAIN FOR DYAKONOV SURFACE WAVES USING THE POCKELS EFFECT

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Abstract

The propagation of Dyakonov surface waves (DSWs) at the planar interface between an isotropic material and a linear electro-optic birefringent material can be dynamically controlled using the Pockels effect. The range of directions for DSW propagation has been previously found to be rather narrow. By careful choice of various parameters, this range of directions can be increased by more than an order of magnitude.

Key words: angular existence domain, Dyakonov surface wave, electro-optics, Pockels effect

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1 Introduction

Electromagnetic surface waves at the planar interface of two different materials travel along a direction parallel to the interfacial plane with decaying amplitudes perpendicular to the direction of propagation in both materials. Research on surface-wave propagation can be traced back to about a century ago to Zenneck [1] and continues to be of technoscientific importance [2].

In recent years, Dyakonov surface waves (DSW) have attracted much attention [3]. These waves can exist at the planar interface of an isotropic material and a uniaxial material, both dielectric, as was shown first by D'yakonov [4] and then enlarged upon by Averkiev and Dyakonov [5]. The isotropic material is not metallic. Later, several researchers considered DSW propagation on increasingly complex bimaterial interfaces such as biaxial-isotropic, uniaxial-uniaxial, and biaxial-biaxial materials—see, e.g., Refs. 6–10.

DSW propagation is assured when a dispersion equation is satisfied. This equation arises from having to satisfy the frequency-domain Maxwell postulates in both materials as well as the boundary conditions at the interface. Therefore, DSW propagation depends highly on the crystallographic symmetries of the two materials, at least one of which must be birefringent. Calculations for many pairs of materials have shown that conditions for DSW propagation are favored only for a narrow and restricted angular range of propagation directions in the interface [3, 7, 10, 11, 12, 13]. The width of this angular existence domain (AED) is denoted here by $\Delta\psi$. With the exception of some interfaces involving hypothetical metamaterials [12], $\Delta\psi$ for interfaces of non-magnetic materials are small — in most cases, only a fraction of a degree [3]. This makes experimental observation of DSW propagation very difficult. One of the largest values of $\Delta\psi$ has been calculated to be $\approx 4^\circ$ [3]; however, in that case one of the materials is calomel, a chalky and dusty material that is impractical to use.

The potential real-life applications envisaged for the use of DSW are numerous [3], including devices for integrated optics, chemical and biological surface sensing, etc. To be able to experimentally launch a DSW, to experimentally detect a DSW, and to possibly control the DSW characteristics, a sufficiently wide AED appears desirable. That desire motivated this communication.

In a predecessor paper [14], we looked at the control of DSW propagation at the interface of an electro-optic material, potassium niobate, and an isotropic material through application of an external dc electric field. Now, we examine optimizing the width $\Delta\psi$ of the AED by an exploration of the effects of: the crystal orientation, the direction of applied dc electric field, and the strength of the applied dc electric

field. Considering the planar interface of an isotropic and a birefringent material, both dielectric, we show in Sec. 2 that $\Delta\psi$ can be increased by a large factor—if the birefringent material is susceptible to the Pockels effect—by suitable choices of parameters such as the magnitude and orientation of an applied dc electric field, the crystallographic orientation of the birefringent material in relation to the interface, and the refractive index of the isotropic material.

2 Preliminaries and Numerical Results

We considered the following problem [14]. The half-space $z < 0$ is filled with a homogeneous, isotropic, dielectric material with an optical refractive index denoted by n_s . The half-space $z > 0$ is filled with a homogeneous, linear, electro-optic material, whose optical relative permittivity matrix is stated as

$$\bar{\epsilon}_{rel} = \bar{S}_z(\psi) \cdot \bar{R}_y(\chi) \cdot \bar{\epsilon}_{PE} \cdot \bar{R}_y(\chi) \cdot \bar{S}_z(-\psi) . \quad (1)$$

Incorporating the Pockels effect due to an arbitrarily oriented but uniform dc electric field \underline{E}^{dc} , the matrix $\bar{\epsilon}_{PE}$ is given by

$$\bar{\epsilon}_{PE} \approx \begin{pmatrix} \epsilon_1^{(0)}(1 - \epsilon_1^{(0)}s_1) & -\epsilon_1^{(0)}\epsilon_2^{(0)}s_6 & -\epsilon_1^{(0)}\epsilon_3^{(0)}s_5 \\ -\epsilon_1^{(0)}\epsilon_2^{(0)}s_6 & \epsilon_2^{(0)}(1 - \epsilon_2^{(0)}s_2) & -\epsilon_2^{(0)}\epsilon_3^{(0)}s_4 \\ -\epsilon_1^{(0)}\epsilon_3^{(0)}s_5 & -\epsilon_2^{(0)}\epsilon_3^{(0)}s_4 & \epsilon_3^{(0)}(1 - \epsilon_3^{(0)}s_3) \end{pmatrix} , \quad (2)$$

correct to the first order in $|\underline{E}^{dc}|$, where

$$s_j = \sum_{K=1}^3 r_{jK} E_K^{dc} , \quad j \in [1, 6] , \quad (3)$$

$$\begin{pmatrix} E_1^{dc} \\ E_2^{dc} \\ E_3^{dc} \end{pmatrix} = \bar{R}_y(\chi) \cdot \bar{S}_z(-\psi) \cdot \begin{pmatrix} E_x^{dc} \\ E_y^{dc} \\ E_z^{dc} \end{pmatrix} , \quad (4)$$

$\epsilon_{1,2,3}^{(0)}$ are the principal relative permittivity scalars in the optical regime, whereas r_{JK} (with $1 \leq J \leq 6$ and $1 \leq K \leq 3$) are the electro-optic coefficients. The electro-optic material can be isotropic, uniaxial, or biaxial, depending on the relative values of $\epsilon_1^{(0)}$, $\epsilon_2^{(0)}$, and $\epsilon_3^{(0)}$. Furthermore, this material may belong to one of 20 crystallographic classes of point group symmetry, in accordance with the relative values of the coefficients r_{JK} .

The rotation matrix

$$\bar{S}_z(\psi) = \begin{pmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (5)$$

in Eq. (1) denotes a rotation about the z axis by an angle $\psi \in [0, 2\pi)$. The matrix

$$\bar{R}_y(\chi) = \begin{pmatrix} -\sin \chi & 0 & \cos \chi \\ 0 & -1 & 0 \\ \cos \chi & 0 & \sin \chi \end{pmatrix} \quad (6)$$

involves the angle $\chi \in [0, \pi/2]$ with respect to the x axis in the xz plane, and combines a rotation as well as an inversion. The angles ψ and χ delineate the orientation of the electro-optic material in the laboratory coordinate system, the full transformation from laboratory coordinates (x, y, z) to those used conventionally for electro-optic materials (1, 2, 3) being illustrated by Nelatury *et al.* [14].

The wave vectors on both sides of the interface were taken to lie wholly in the xz plane. The field representations based on the Maxwell curl postulates in the two half-spaces, the boundary conditions at the interface $z = 0$, and the dispersion equation for DSW propagation are available elsewhere [14]. For a simple case like that of the isotropic-uniaxial interface, obtaining a closed-form expression for $\Delta\psi$ is relatively easy. However, for complex cases such as the one we are treating here, that goal is perhaps impossible. Recourse, then, has to be made to numerical methods in order to mount an extensive search for the proper choice of parameters that allow DSW propagation.

A search was carried to maximize $\Delta\psi$ in relation to the magnitude and the direction of the dc electric field, the refractive index of the substrate, and the tilt angle χ . Potassium niobate was chosen as the electro-optic material, because the magnitudes of its electro-optic coefficients are very large.

Table 1 shows χ and n_s values in a neighborhood wherein $\Delta\psi$ is a maximum. Figure 1 shows the variation of $\Delta\psi$ with n_s for $\chi = 58.06^\circ, 58.08^\circ$ and 58.099° . The dc electric field is $\underline{E}^{dc} = \hat{z} 1.2 \times 10^7 \text{ V m}^{-1}$. We found that, around $\chi = 58^\circ$, even a small change in χ produces a large change in $\Delta\psi$. The last entry in Table 1 shows $\Delta\psi \approx 1.4^\circ$ which is 20 times larger than the result previously reported by us [14].

The search for a wider AED was also attempted choosing \underline{E}^{dc} parallel to $-\hat{z}$, $\hat{x} \cos \psi + \hat{z} \sin \psi$ and $-\hat{x} \sin \psi + \hat{z} \cos \psi$ for the same choices of n_s and χ values. But we could get only $\Delta\psi$ of order 0.02° . However, we wish to continue the search hoping for wider AED.

χ	n_s	$\Delta\psi$
58.05°	2.2805	0.7312°
58.06°	2.2804	0.7805°
58.07°	2.2804	0.8179°
58.08°	2.2803	0.9761°
58.09°	2.2802	1.0302°
58.099°	2.2801	1.4°

Table 1: Maximum $\Delta\psi$ for some choice of parameters.

3 Concluding Remarks

In summary, Dyakonov surface waves propagate along interfaces involving birefringent materials over a narrow angular range $\Delta\psi$ of the orientation angle ψ . Having a larger $\Delta\psi$ is helpful for easier generation and detection of DSWs. Several attempts have been made to widen this angular existence domain. By considering specific directions of an applied dc electric field and specific values of χ , we have shown that exploitation of the linear electro-optic (Pockels) effect has the potential to widen the AED. The search for higher values of $\Delta\psi$ for an arbitrarily oriented dc electric field is still open. Also, one might look into ranges of χ values for specific values of ψ and various magnitudes and directions of the applied dc electric field.

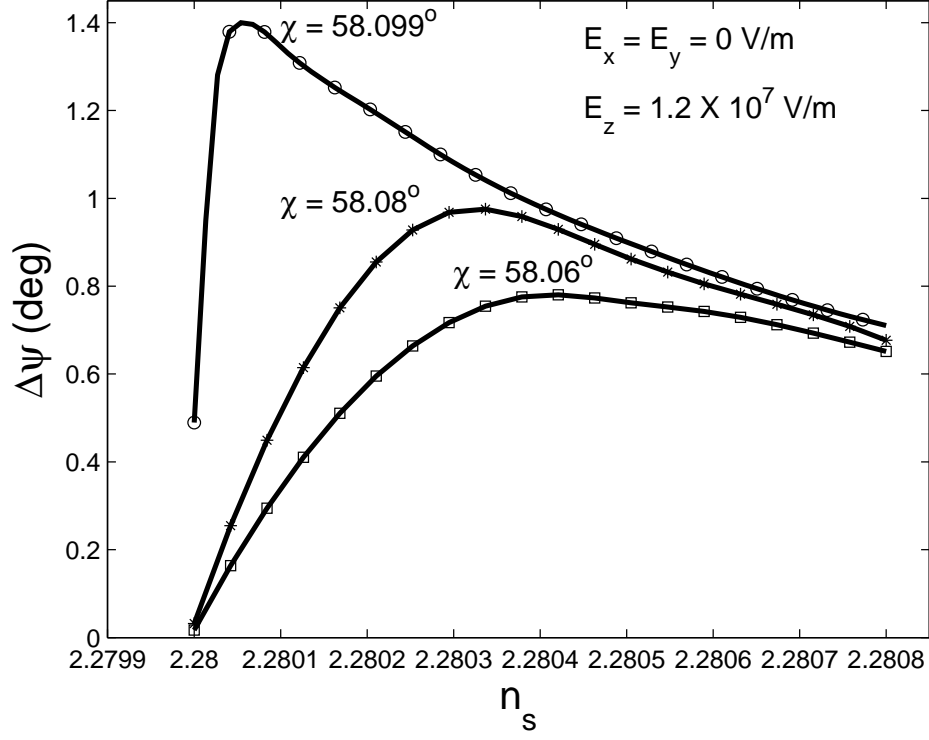


Figure 1: Variation of $\Delta\psi$ versus n_s for different χ values

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